AD703247

Project THEMIS

CONTRACT ONR-N00014-68-A-0152

University of Notre Dame
college of engineering
notre dame, indiana

46556

MAGNETOSTRICTION AND MAGNETIC ANISOTROPY
IN SOME IRON RICH
IRON-COBALT-ALUMINUM ALLOYS

by

M. Kuruzar, M. Phadke
and
A. E. Miller

Febr̄. y, 1970

Project THEMIS
UNIVERSITY OF NOTRE DAME
College of Engineering
Notre Dame, Indiana   46556

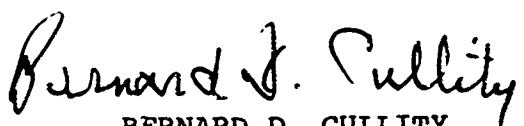TECHNICAL REPORT
NUMBER:
THEMIS-UND-70-6

FOREWORD

This technical report was prepared by the Magneto-
mechanical Systems Group under Project THEMIS at the
University of Notre Dame, College of Engineering.
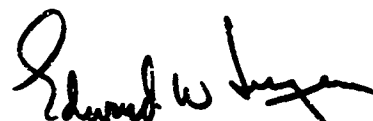
Readers are advised that <u>reproduction in whole or
in part is permitted for any purpose of the United States
Government.</u>

This technical report has been reviewed and approved
for submittal to the sponsoring agency on February 25, 1970.

BERNARD D. CULLITY
Group Leader
Magnetomechanical Systems

EDWARD W. JERGER
Program Manager
Project THEMIS

JOSEPH C. HOGAN
Dean, College of Engineering
University of Notre Dame

ABSTRACT

The magnetic anisotropy and magnetostriction of single
crystals and the magnetostriction of some polycrystalline
specimens of several Fe rich Fe-Co-Al alloys has been experi-
mentally determined. Specialized apparatus and procedures
for alloy preparation, single crystal growth, crystal cutting,
crystal orientation, magnetization and magnetostriction
studies have been developed.

The first anisotropy constants, K_1, for 75Fe-15Co-10Al
(wt.%), 85Fe-10Co-5Al, 80Fe-10Co-10Al and 80Fe-15Co-5Al alloys
were found to be 79,000, 2,000, 282,000, and 39,000 (ergs/cc),
respectively; the λ_{100} values were found to be $+3.5 \times 10^{-6}$,
$+10.6 \times 10^{-6}$, $+19.4 \times 10^{-6}$, and $+17.5 \times 10^{-6}$, respectively; and the
λ_{111} values were found to be $+6.2 \times 10^{-6}$, -5.6×10^{-6}, $+9.5 \times 10^{-6}$,
and -4.9×10^{-6}, respectively.

TABLE OF CONTENTS

LIST OF FIGURES

I. INTRODUCTION

1-1 General

Magnetostriction is a term that is used to describe the dimensional changes of a ferromagnetic material when it is subjected to a magnetic field or, conversely, the change in the material's magnetic properties when its dimensions are altered by an externally applied stress. Devices, in which these materials are coupled to an alternating magnetic field, are of great technological importance since they form the basis for echo-sounding and nondestructive testing systems as well as ultrasonic cleaning, drilling and cutting units.

Although a detailed discussion of the basic phenomenom of ferromagnetism and magnetostriction is beyond the scope of this report and definitive works in the field [1], [2], and [3] should be consulted if a deeper understanding is desired, nevertheless, it is appropriate to elucidate briefly a couple of terms that are frequently used in this report.

1. Longitudinal Magnetostriction. A measure of a ferromagnetic materials sensitivity to the magnetostriction effect is the magnitude of the strain λ (defined as $\Delta\ell/\ell$, where ℓ is the original length) experienced by the material in the direction of an applied magnetic field. Longitudinal magnetostrictive strain, λ, may be either positive or negative, indicating an expansion or a contraction in the direction of the magnetic field respectively.

2. Saturation Magnetostriction. The longitudinal
   magnetostrictive strain reaches a maximum, con-
   stant value at some value of applied magnetic
   field. This maximum in λ is called the satu-
   rated value, λ_s.

3. Magnetocrystalline Anisotropy. In a single
   crystal of a ferromagnetic material there is
   a preferred crystallographic direction along
   which the intrinsic magnetization lies. The
   energy, called anisotropy energy, required
   to turn the magnetization vector out of the
   preferred direction is indicated by a general
   anistropy constant, K.

The ferrite ceramics [4], nickel and nickel base [5]
alloys are in common use today as magnetostrictive trans-
ducer elements. These materials have λ_s values from
30×10^{-6} in/in to 150×10^{-6} in/in with the metallic phases
occupying the lower end of the range. These materials face
tough competition in the transducer field from ceramic
piezoelectric materials which have electrostrictive strains
three orders of magnitude larger than the λ_s of the magneto-
strictive materials [6]. However, ceramic materials in
general suffer from two serious shortcomings:

1) they are brittle and have a low resistance
   to impact loads, and
2) they have a high notch sensitivity and very
   poor fatigue resistance.

Hence, the metallic magnetostrictive materials offer
definite advantages since they are vastly superior to ceram-
ics in the above areas. They are, however, somewhat limited

in their application due to the fact that λ_s is usually not as large as required by the device application. The greatly superior reliability of a transducer device constructed with metallic active elements certainly merits an expenditure of effort to develop alloys with larger and more useful values of λ_s.

1-2 Metallurgical Parameters to be Considered

The development of metallic alloys for magnetostrictive transducer applications is a many faceted undertaking that requires the simultaneous optimization of several different but interdependent metallurgical variables; e.g., alloy content, texture, residual stress, etc. This type of optimization of variables is commonly encountered in engineering and at best is a very tedious task even in those situations where reasonably accurate theories exist from which the important parameters and their interrelations can be extracted. In the case of magnetostriction, where a complete understanding of the fundamental processes involved in the phenomenon is lacking, it is difficult to establish and optimize the controlling parameters for the most simple case, that of a pure metal, and it becomes extraordinarily difficult to predict the effects of alloying on these parameters. Hence, it becomes necessary to begin by studying a simple model from which 1) some of the controlling parameters can be more definitely established, 2) some simple interrelations between these parameters can be deduced; and 3) the course of the research program can be outlined.

If a magnetostrictive device, such as the one shown schematically in Figure 1.1, is considered as a unit with the primary function of converting electrical work into
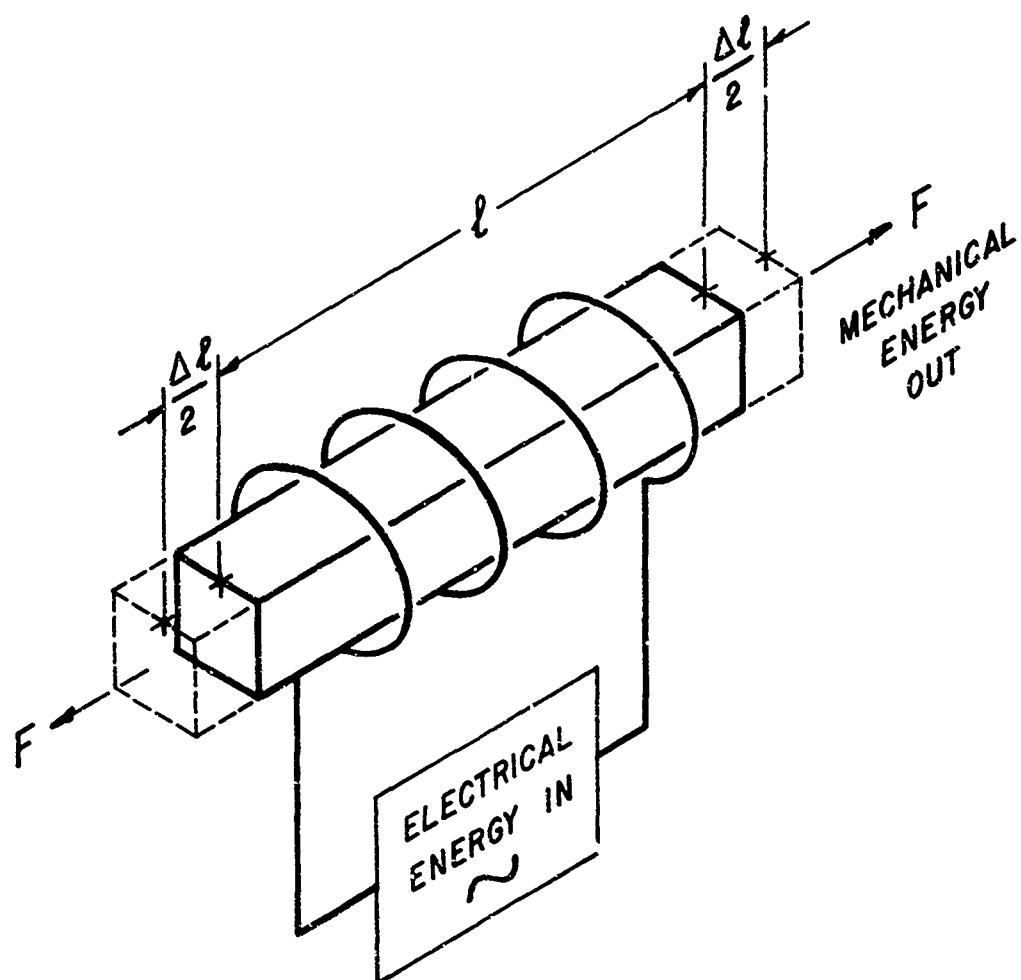
Figure 1.1   A Magnetostrictive Transducer
as an Energy Conversion Device

mechanical work or vice versa, then good design principles
dictate that 1) the mechanical work out of the system
should be as large as possible and 2) the efficiency of the
unit in converting electrical work into mechanical work
should be a maximum. Assuming that a fictitious "magneto-
strictive force", F, "produces" the change in length, $\Delta\ell$,
of the magnetostrictive element with a zero field length, ℓ,
upon the application of an axial magnetic field, then the
mechanical work done by the magnetostrictor is,

$$F \times \Delta\ell$$

and since $E = F/A / \Delta\ell/\ell$ where E is the elastic modulus and
A is the cross sectional area normal to the force,

then $Work_{Mech} = A\ell E \left(\frac{\Delta\ell}{\ell}\right)^2$

and $Work_{Mech} / \begin{array}{l} \text{Volume of} \\ \text{Material} \end{array} = E \left(\frac{\Delta\ell}{\ell}\right)^2 = E(\lambda)^2.$

Now that the form of the output work has been estab-
lished the electrical input work can be described as a sum
of terms:

1)   the work done against the "magnetostrictive
      force" = $E(\lambda)^2$,
2)   the work done against magnetocrystalline
      anisotropy = K,
3)   the work that is done to counteract the
      effect of internal residual stresses,
      $\sigma_{R'} = \sigma_R \lambda$,
4)   the work that must be done to overcome the
      demagnetizing effects arising from the
      presence of free magnetic poles as the re-
      sult of voids, nonmagnetic inclusions or

microcracks = $f(\rho)$, where $f(\rho)$ indicates
that the work required is a function of the
number and distribution of the free mag-
netic poles.

Hence, the efficiency of the device in going from zero field
to some static applied magnetic field is:

$$Eff = \frac{E(\lambda)^2}{E(\lambda)^2 + K + \sigma_R\lambda + f(\rho)}.$$

From the above expression for efficiency deduced o:
the basis of the simple model discussed it is now possible
to focus attention on those metallurgical parameters that
are of obvious importance. First, the term, $\sigma_R\lambda$, has a
deleterious effect on the efficiency but can be eliminated
by adopting rather standard metallurgical annealing prac-
tices used for internal stress relief. Second, $f(\rho)$, can
also be reduced to a negligible value by using reasonable
care in material preparation and in subsequent forming oper-
ations. Third, the anisotropy energy, K, is an intrinsic
property of the material as are λ and E, all of which are a
function of the composition of the material. Thus, it ap-
pears that the objectives of alloying to produce better
transducer material characteristics should be to 1) maximize
λ and E so that the magnitude of the mechanical work that
the device can do is as large as possible and 2) minimize
K so as to obtain the highest possible efficiency.

In the above analysis, only the static field situa-
tion was developed because of its simplicity and also since
little is to be gained by complicating the model by intro-
ducing an oscillating magnetic field. However, the techno-
logically important applications of magnetostrictive
materials are to devices that operate in a cyclic manner and

produce vibratory mechanical work. This cyclic operation introduces at least two other losses that must be considered
- hysteresis and eddy current losses. However, in general it is found that alloying to minimize K also increases permeability and decreases the size of the hysteresis loop. In order to reduce the eddy currents it would be desirable to alloy to increase resistance, which would in turn increase flux penetration and reduce hysteresis losses, but this is not usually profitable since in many cases the effects are not large and in those cases where they are serious complicating factors arise; e.g., λ_s becomes very small, or extremely brittle, ordered phases exist. Similar complications are encountered if alloying is performed to maximize E. Thus, in the final analysis it can be said that the primary objectives of a program to develop better magnetostrictive metallic alloys should be to control alloy content so as to maximize λ_s and minimize K.

1-3 Selecting an Alloy System

A survey of the literature [7], [8], [9] concerning magnetostriction indicates that the addition of either aluminum or cobalt to iron increases the saturation magnetostriction, λ_s, in the [100] direction to values that are larger than the reported λ_s for nickel, Figure 1.2. It is interesting to speculate that the observed increase in λ_s produced by alloying the individual elements Al and Co with Fe could be additive in such a manner that an Fe-rich Fe-Co-Al alloy exists that has a λ_s larger than that displayed in either of the binary systems. However, as shown in Figure 1.3, the anisotropy constants for both Fe-Co and Fe-Al alloys are positive [7] thus making it rather unlikely that too much could be gained in this respect. But, since λ_s appears as a squared term it was felt that the possibility
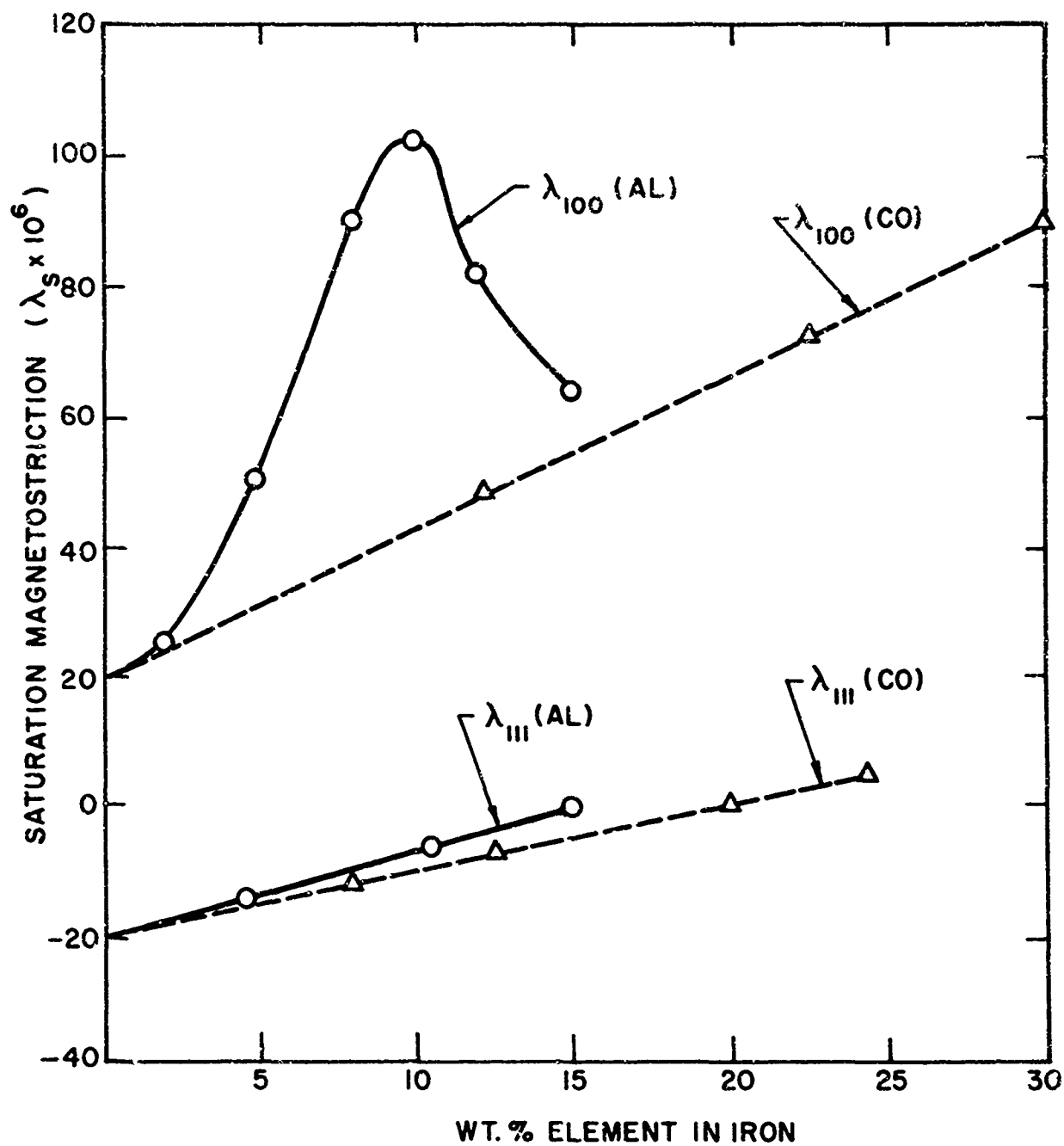
Figure 1.2   Saturation Magnetostriction in the [100] and
             [111] Crystallographic Directions of Cobalt
             and Aluminum Alloys with Iron
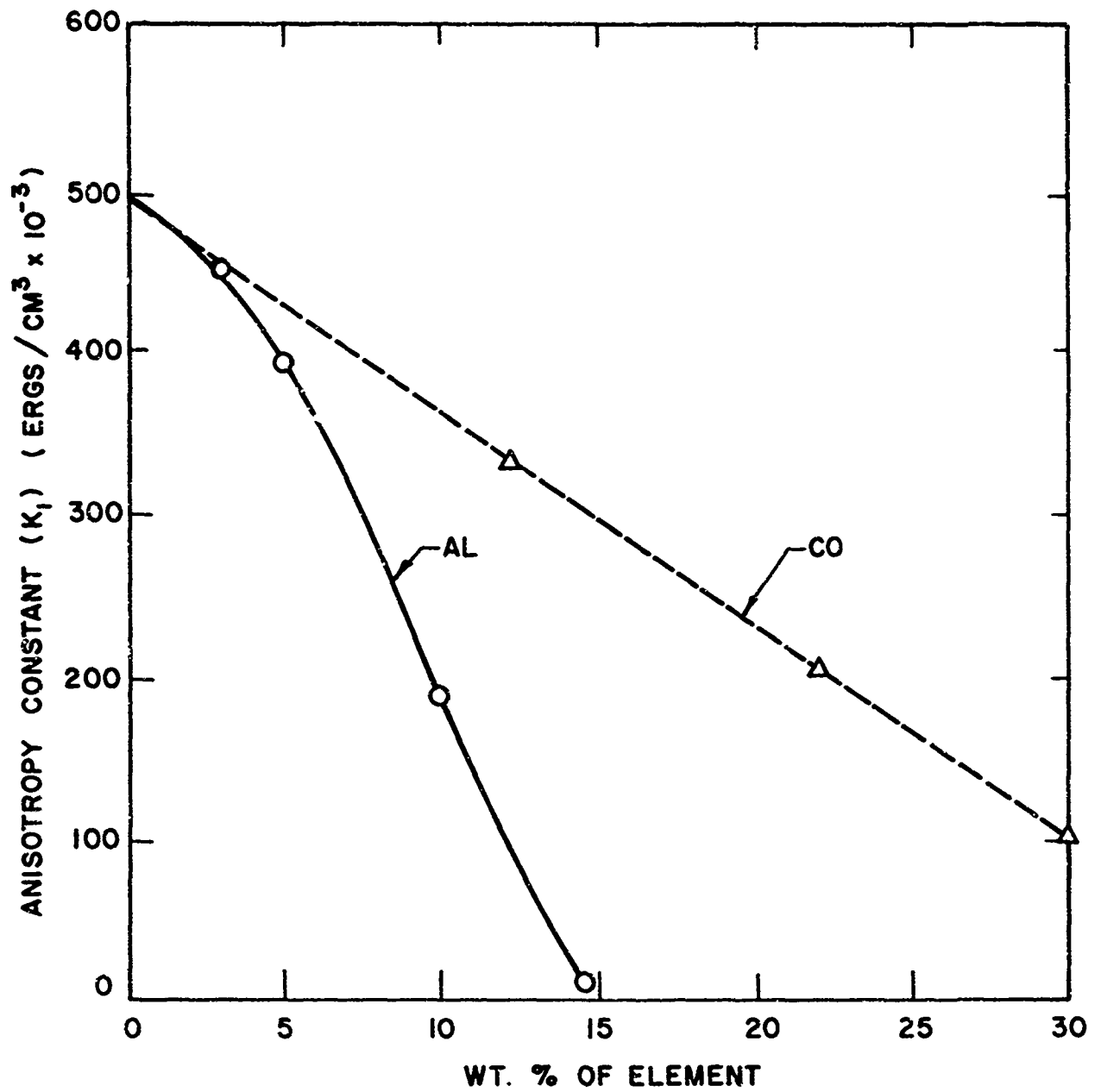
Figure 1.3   Magnetic Anisotropy in Cobalt
and Aluminum Alloys with Iron

of increasing λ_f takes precedence and hence it was decided to study the solid solution alloys in the Fe-rich corner of the Fe-Co-Al system.

II. EXPERIMENTAL PROCEDURE

2-1 Materials

The iron, cobalt and aluminum used in this study were obtained from Crucible Steel, United Mineral and Chemical Corp., and Aluminum Corporation of America, respectively. The major impurities in these materials are shown in Table 2.1.

Table 2.1 Major Impurities in Starting Materials in ppm

Ferrovac E Iron		Aluminum		Cobalt	
Ni	350	Cu	20	Ni	25
Si	<300	Fe	30		
Cu	<100	Si	20		
Cr	<100				
S	50				
C	40				
Al, P, Mn, Mg, Ca <30					

2-2 Preparation of Polycrystalline Samples

All of the alloys, single crystal and polycrystalline, used in this study were initially formed by arc melting weighed amounts of the constituents in a He atmosphere. To do this, it was necessary to design and construct the inert-atmosphere, nonconsumable tungsten electrode, arc-melting system diagrammed in Figure 2.1. This unit facilitates the production of 1 in. diameter by 1/4 in. thick, 30 gm. buttons

Water in

To helium tank

Water out

To vacuum pump

Water cooled electrode mount

Flexible neoprene vacuum joint

Neoprene vaccum seals to pyrex

Pyrex

Tungsten electrode

Water cooled brass shield

Molds in hearth

Water cooled copper hearth

"O"-Ring seals

Water outlets

Water inlet

Tungsten electrode

Sample

−

+

High frequency arc stabilizer

400 Amp. D.C. Supply

Figure 2.1   Diagram of the Arc-Melter used for preparation of Fe-Co-Al Alloys

and has a trough in the water cooled copper hearth for
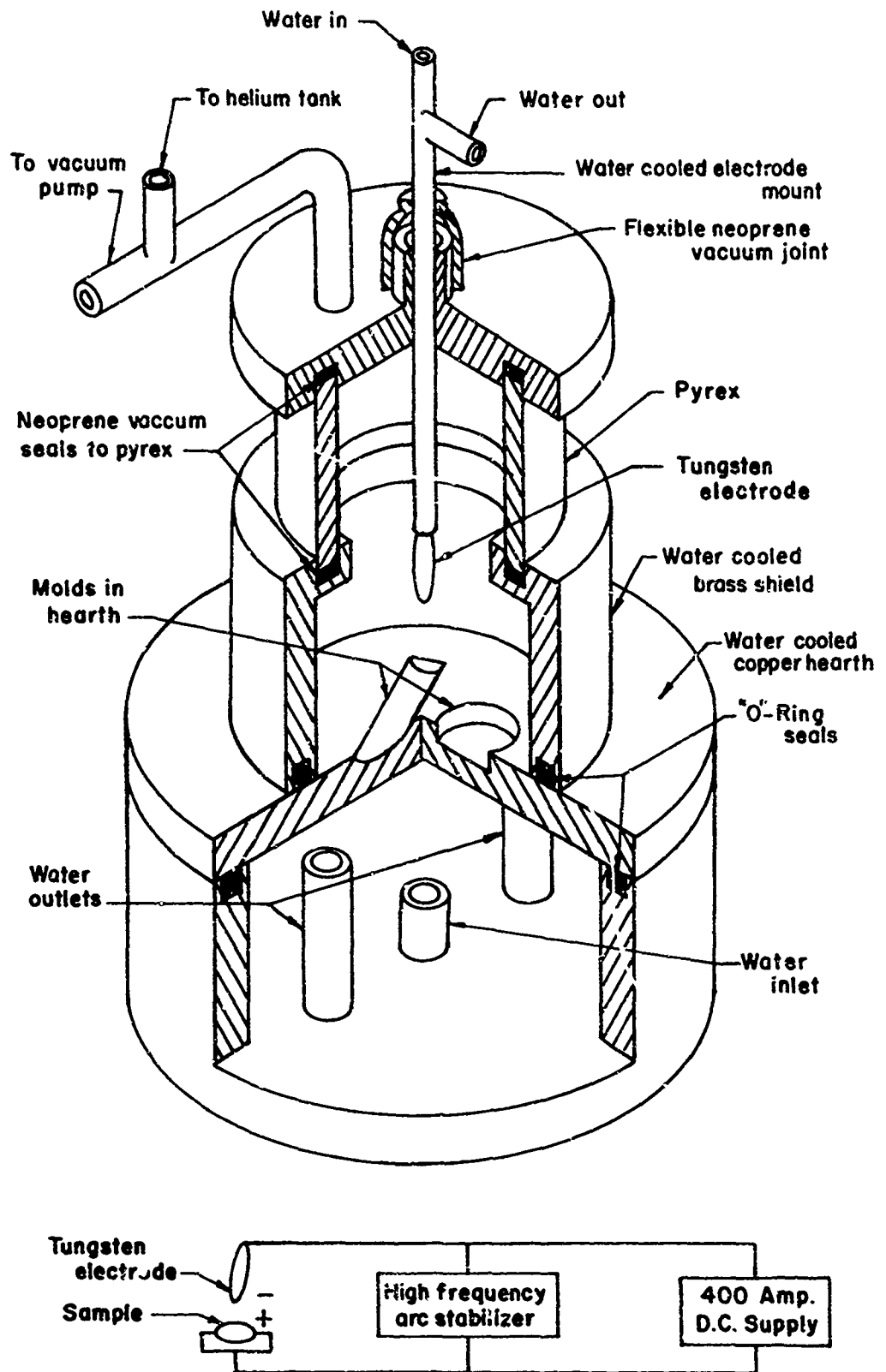the formation of 1/4 in. x 1/4 in. x 3-1/4 in. billets.

The materials were degreased with acetone, pickled
(Fe and Co in dilute sulfuric acid and Al in Tucker's etch)
and dried before weighing. The constituents were placed in
the circular depression in the copper hearth; the system was
then evacuated to about 10 microns of Hg and back-filled
with He gas. The arc was established between the sample and
the water cooled cungsten electrode and "played" over the
material until a molten pool was formed that contained all
of the added material. In order to insure thorough mixing
of the constituents the alloy "buttons" were turned and re-
melted from the opposite side several times. The buttons
were then transferred to the trough and melted into a rod
shape. Weight losses due to vaporization during the alloy
formation were negligible and the alloys were taken to have
the initially calculated composition. Compositions of al-
loys prepared and studied in the program are listed in
Table 2.2.

Table 2.2 Composition of Alloys Studied in wt. %

Constituent	Fe	Co	Al	Sample Number
	75	10	15	1
	75	15	10	2 *
	85	10	5	3 *
	75	20	5	4
	80	10	10	5 *
	80	15	5	6 *

*Indicates compositions that were also prepared and studied
in single crystal form.

In an attempt to break up the as-cast structures the

alloy billets were cut into rectangular parallelopipeds and
subjected to alternate 1% reductions in thickness by cold
rolling operations followed by 2 hr. anneals in argon at
610°C with subsequent furnace cool. This schedule was con-
tinued up to a total reduction in thickness of about 10%
above which alloys 1, 2, 4, and 6 invariably developed
large cracks. Alloys 3 and 5 were hot rolled in the 900-
1100°C range where it was found that reductions in thickness
of 40-60% could be readily obtained in only a few passes
through the rolling mill.

2-3 Preparation of Single Crystal Samples

Single crystals of the ternary alloys noted in Table
2.2 were grown from the melt by the Bridgman technique. In
the modification of this technique employed in this work a
molten charge contained in a stabilized Zirconia crucible
was lowered out of the hot zone. The bottom of the crucible
was tapered and as the taper emerged from the hot zone a
single seed nucleated at the point of the taper and this
single seed continued to grow as the sample was extracted.
Single crystals 3/8 in. in diameter and 2 in. long were pro-
duced with regularity at a withdrawal rate of 2 in./hr.

The vacuum furnace diagrammed in Figure 2.2 was con-
structed for the purpose of crystal growth. The heater
element is a reactor grade graphite spiral 12 in. long with
a bore of 1-1/2 in. With the tantalum radiation shields in
place a uniform hot zone, 5°C maximum variance, about 4 in.
long was obtained at 1500°C and 1×10^{-5} torr.

The charge was observed with an optical pyrometer
through the viewing port on the top of the vacuum chamber.
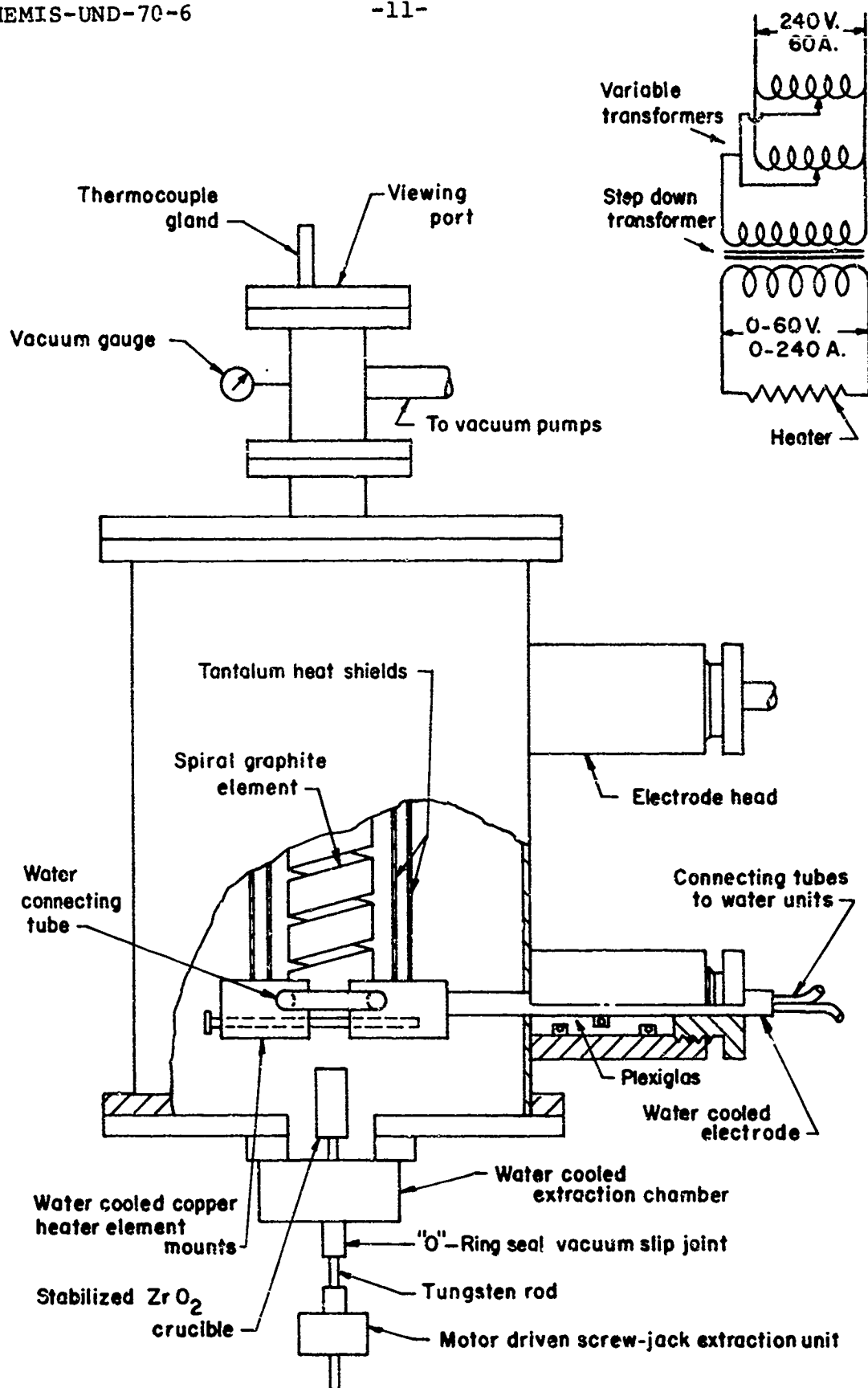After the charge was observed to melt on heating, the sample

Figure 2.2 Diagram of the Vacuum Furnace used for Growth of Fe-Co-Al Alloy Single Crystals

higher than where the melting was first observed. After the
sample had been extracted the furnace was slowly cooled.

The single crystal rods were aligned by an X-ray Laue
technique and placed in a Servo-Met spark cutter. Single
crystal discs about .020 in. thick and 3/8 in. in diameter
were cut parallel to the {110} planes within about ± 2°.
The discs were spark planed to obtain smooth and parallel
surfaces, and annealed at 550°C for about 2 hours to relieve
any possible strains induced by spark machining.

2-4 X-Ray and Metallographic Methods

Standard powder X-ray diffraction techniques were
used to verify the single phase, body-centered cubic nature
of all the alloys studied. Powder for the analysis was ob-
tained by filing the specimens with a hardened steel file.
The powder was sealed in a glass capillary and exposed to
Cr K_α radiation. The sharpness of the resulting patterns
indicated that it was unnecessary to anneal the powder be-
fore taking a pattern.

The crystallographic texture at various positions
along the length of the polycrystalline samples was deter-
mined from integrated intensity measurements of the (200)
and (110) diffraction lines using an X-ray diffractometer
with a 1° incident slit and Cr K_α radiation. The sample
surfaces were first polished and then chemically milled
with 2 pct. Nital to remove any possible cold work effects
produced by polishing. The observed integrated intensity
ratio of $I_{(200)}/I_{(110)}$ was then compared to the predicted
value of $I_{(200)}/I_{(110)} = 1/5$ for a random orientation. This
technique was used to follow the effect of various treat-
ments on the texture of the specimens.

The back reflection Laue method was used to align all single crystals. The Laue spots obtained were sharp and singular indicating the lack of residual strains and low angle grains.

Standard metallographic procedures were used to prepare the alloys for microscopic examination. The alloys were etched using a 20 sec. dip in 50% H_2SO_4 followed by a 10 sec. dip in 3% Nital.

2-5 Magnetic Measurements

Magnetostriction studies of the polycrystalline samples were made with the set-up shown in Figure 2.3. SR-4 type strain gauges were attached to parallelopiped samples about 1/4" x 1/4" x 3" in size. The sample was placed in a solenoid of known current-magnetic field characteristics with the long dimension along the axis of the solenoid. The solenoid current was changed in convenient incruments and the resulting strain was measured on a BAM-1* strain gauge bridge. After each strain measurement the DC supply to the solenoid was disconnected and the output of an AC variable transformer was connected. The AC voltage across the solenoid was then increased to a predetermined value and returned to zero. During this operation the sample was exposed to a steadily decreasing 60 hz magnetic field that served to demagnetize the specimen. After demagnetizing the specimen, the variable transformer was replaced by the DC power supply, the solenoid was energized to a predetermined level and the measurement procedure repeated.

---

*Model BAM-1, Bridge Amplifier and Meter manufactured by Ellis Associates, Pelham, New York.

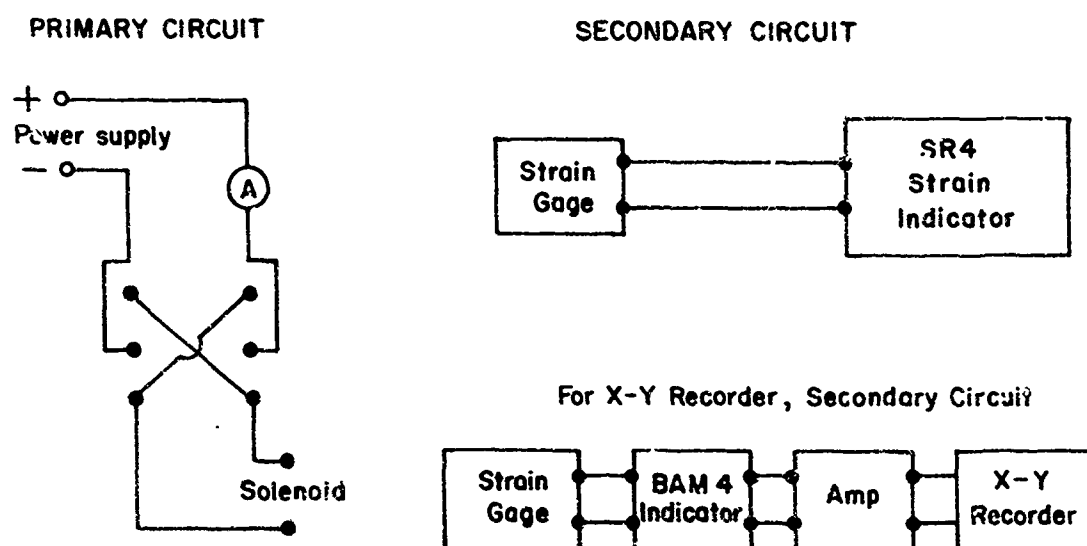PRIMARY CIRCUIT   SECONDARY CIRCUIT

Figure 2.3   Schematic of System used to
Measure Magnetostriction

A strain gauge technique similar to that described
above, Figure 2.3, was used for the magnetostriction studies
of the single crystals. Strain gauges were placed on the
crystals in the [100], [111], and [110] crystallographic
directions. Magnetostriction was plotted for each gauge
direction for different field directions. The angle θ,
defined as the angle between the [100] crystallographic di-
rection and the field direction, was varied from 0 to 180°
in 10° increments.

The magnetic anisotropy was determined from magneti-
zation vs. applied field curves automatically plotted for
the [100], [111], and [110] crystallographic directions by
a vibrating-sample magnetometer. The magnetometer construc-
ted for this purpose is shown in Figure 2.4. In this tech-
nique the magnetized sample is vibrated at 102 hz perpen-
dicular to the applied field. The time varying part of the
oscillating dipole field is sensed by pick-up coils suitably
placed in the vicinity of the sample. The output of the
coils, calibrated against the saturation moment of nickel
(54.55 $\frac{emu}{gm}$), was amplified, rectified, and used to drive the
y axis of a function plotter while the output of a Hall ef-
fect device placed in the magnet air gap was used to drive
the applied field or x axis.

III. RESULTS

3.1 X-ray Studies

Metallographic and X-ray examination of the alloys
studied showed that they were one phase solid solutions with
an expanded alpha iron (body-centered cubic) structure,
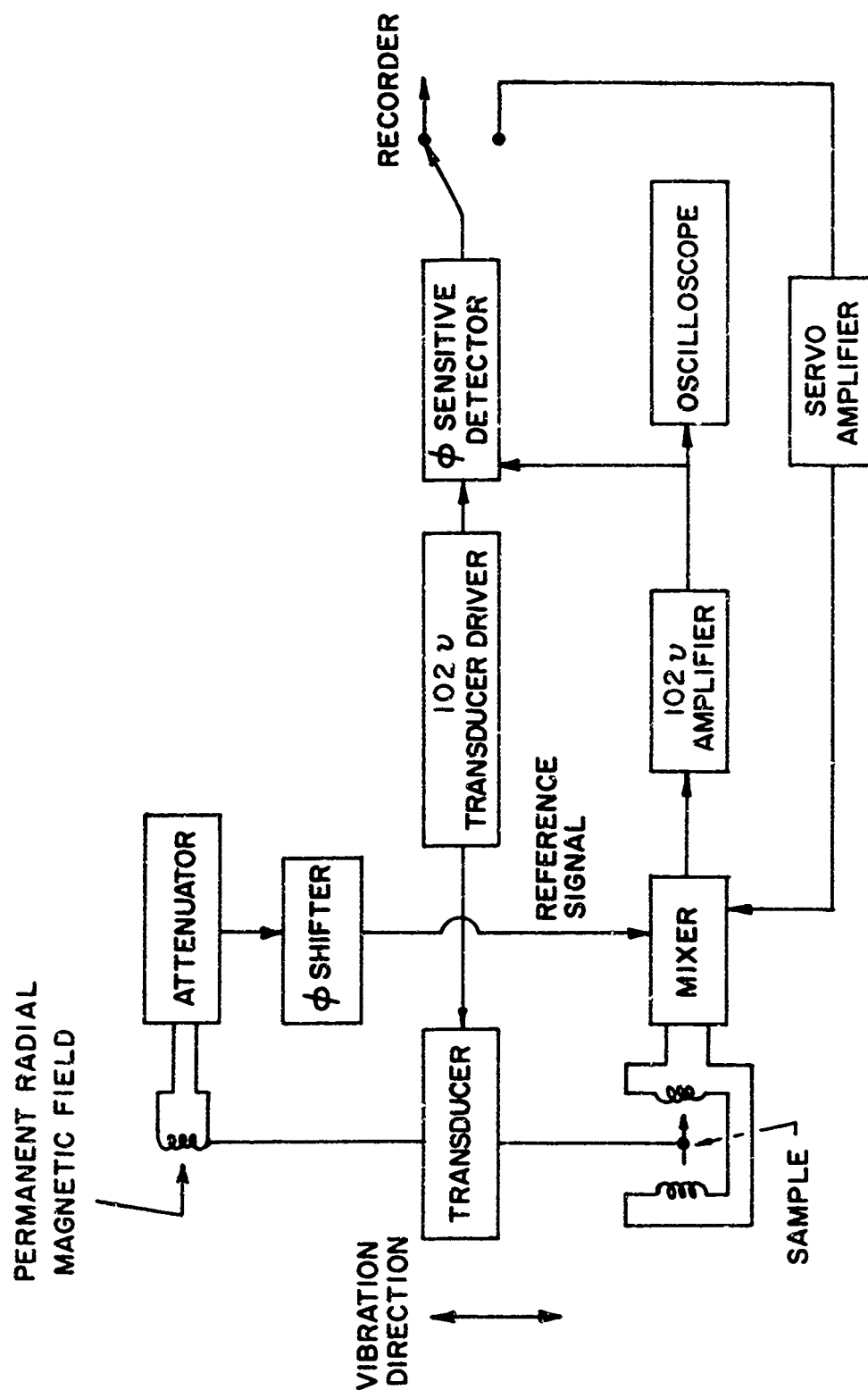Table 3.1.

Figure 2.4   Schematic of a Vibrating-
Sample Magnetometer

Table 3.1   Lattice parameters of single crystal alloys

Composition wt.% Fe-Co-Al	a_o, (A°)
75-15-10	2.882
85-10- 5	2.862
80-10-10	2.890
80-15- 5	2.878

3.2 Texture Studies

Many attempts were made to establish either a schedule of cold rolling and annealing processes or a hot rolling process that would break up the as-cast structure of the arc-melted samples and produce either a randomly oriented polycrystalline material or, more realistically, a material with uniform texture.

However, all such attempts were unsuccessful. This observation is not really too surprising when the following variables involved in the solidification of the arc-melted sample are considered:

1) Texture studies indicated that in general solidification took place with the (110) planes parallel to the copper hearth on the sides that the melt contacted the hearth. On the top side of the sample, however, a very uneven texture was observed.

2) The degree of (110) solidification texture appeared to depend upon:
    a) degree of superheat,
    b) rate at which the arc was moved along the length of the melt, and

c) the manner in which the arc was
   extinguished when melting was
   complete.

These variables were difficult to control and hence despite
all efforts polycrystalline samples with uniform texture
along the sample length were not obtained.

3.3 Magnetostriction Studies

Even though samples of uniform texture could not be
obtained it was none the less instructive to look at the
magnetostriction of one of the more workable alloys. Figure
3.1 summarizes the results obtained for several 85Fe-10Co-
5Al alloys that had been subjected to different mechanical
working and heat treating processes. Although some of the
alloys were hot worked at temperatures from 900 to 1100°C
with reductions in thickness from 30 to 60% while others
were cold worked by various amounts up to 20% followed by
annealling at 800°C, the magnetostriction data lies within
the band indicated. The fact that the band lies very close
to the λ vs. H relation observed for Fe in the [110] direc-
tion indicates that the alloys probably have a strong [110]
texture along the axis of the sample parallel to the mag-
netic field.

Experimentally it is found that the saturation mag-
netostriction measured on single crystals fits the two con-
stant expression:

$$\lambda_s = h_1 (\alpha_1^2 \beta_1^2 + \alpha_1^2 \beta_1^2 + \alpha_1^2 \beta_1^2 - 1/3)$$

$$+ 2h_2 (\alpha_1 \alpha_2 \beta_1 \beta_2 + \alpha_2 \alpha_3 \beta_2 \beta_3 + \alpha_3 \alpha_1 \beta_3 \beta_1)$$
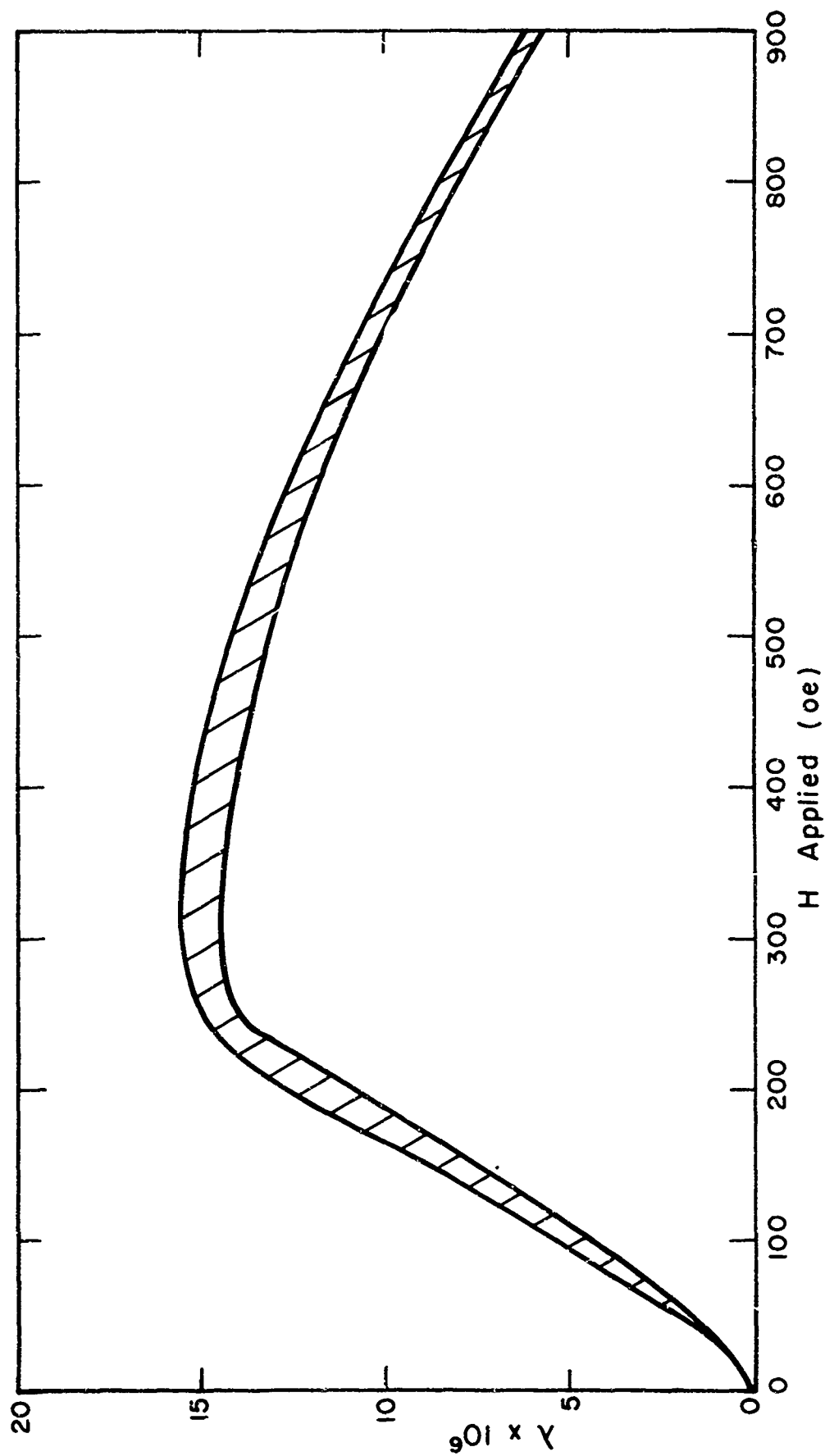
Figure 3.1 Magnetostriction in Cast and
Formed 85Fe-10Co-5Al Alloys

where λ_s is the saturation magnetostriction measured in the crystallographic direction having direction cosines of β_1, β_2, and β_3 with the crystal axis when the crystal is magnetized in a direction having direction cosines of α_1, α_2, and α_3 with respect to the same crystallographic axis. The magnetostriction constants h_1 and h_2 are related to the directional and polycrystalline saturation magnetostriction values:

$$\lambda_{100} = \frac{2}{3} h_1$$

$$\lambda_{111} = \frac{2}{3} h_2$$

$$\lambda_{110} = \frac{1}{6} h_1 + \frac{1}{2} h_2$$

$$\lambda_\rho = \frac{4}{15} h_1 + \frac{2}{5} h_2$$

where λ_{100}, λ_{111}, and λ_{110} are the values in the respective directions and λ_ρ is the value for polycrystalline material with a random grain orientation.

The data was analyzed in a manner similar to that described by Hall [7]. The values of saturation magnetostriction were obtained by extrapolating the magnetostriction versus field strength curves to zero field strength, Figure 3.2. The extrapolated value of magnetostriction at zero field was taken to be the saturation magnetostriction and was used in all further calculations.

There are two experimental situations that simplify the determination of the magnetostriction constants, h_1 and h_2:
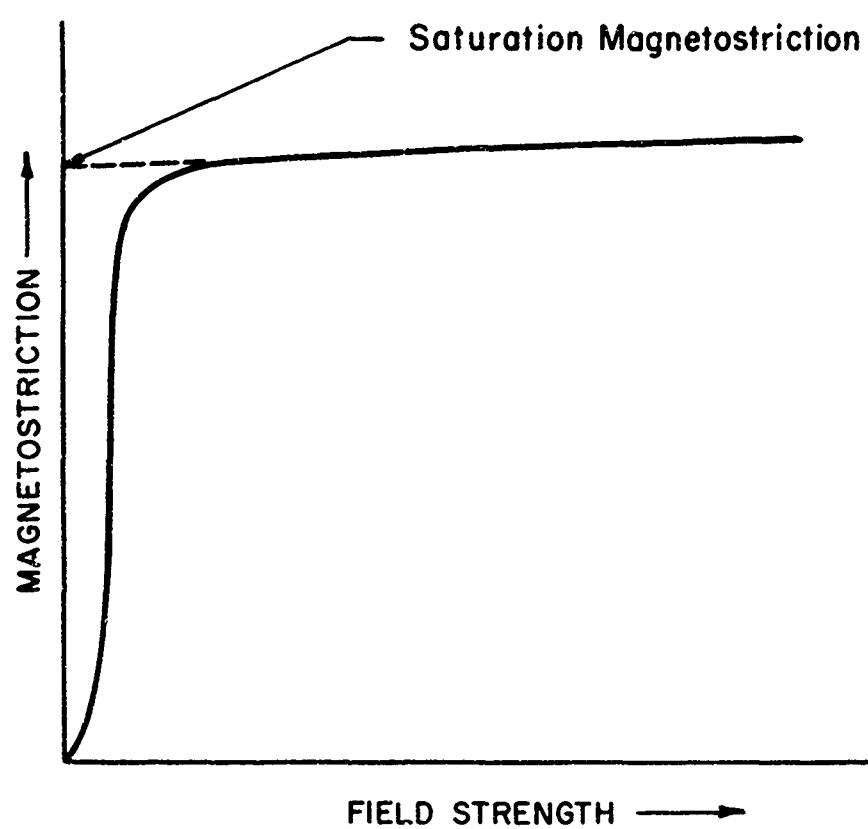
Figure 3.2   Sketch Illustrating the Method used to
              Obtain Saturation Magnetostriction

1) With the strain gauge mounted on a crystal
   whose surface is parallel to the {110}
   planes and the gauge placed so as to
   measure strain in the {100} direction,
   the angular coefficient of the h_2 term
   is zero. Thus a mean value of h_1 can be
   determined from:

$$h \ = \frac{\Sigma \ \lambda \quad (\text{gauges parallel to [100]}, \ \theta = 0 \text{ to } 180)}{\Sigma \ (h \quad \text{coefficients}, \ \theta = 0 \text{ to } 180)}$$

2) With the strain gauge mounted on a crystal
   surface parallel to {110} planes and
   placed so as to measure strain in the [111]
   direction, the angular coefficient of the
   h_1 term is zero. Thus a mean value of h_2
   can be determined from:

$$2h \ = \frac{\Sigma \ \lambda (\text{gauge parallel to [111]}, \ \theta = 0 \text{ to } 180)}{\Sigma (h \ \text{angular coefficients}, \ \theta = 0 \text{ to } 180)}$$

The saturation magnetostriction values obtained as a
function of θ for the various alloys in the [100], [110],
and [111] directions are shown in Figures 3.3 - 3.6. The
data obtained for the saturation magnetostriction for the
[100] and [111] directions were used to determine the magneto-
striction constants h_1 and h_1 as described above. The results
are shown in Table 3.2.

The shape of the sample has a small effect on the
measured magnetostriction and slight corrections to h_1 and
h_2 are usually required. The corrections are given as:

Table 3.2

Saturation magnetostriction values and magnetostriction constants

Composition wt.% Fe-Co-Al	$h_1 \times 10^6$	$h_2 \times 10^6$	$\lambda_{100} \times 10^6$	$\lambda_{111} \times 10^6$	$\lambda_{110} \times 10^6$	$\lambda_p \times 10^6$
75-15-10	+ 5	+ 9	+ 3.5	+6.2	+ 5.5	+ 5.1
85-10- 5	+16	- 8	+10.6	-5.6	- 1.5	+ 0.9
80-10-10	+29	+14	+19.4	+9.5	+11.2	+13.5
80-15- 5	+26	- 7	+17.5	-4.9	+ 0.7	+ 4.0

Figure 3.3   Saturation Magnetostriction Measured in the [100], [110], and [111] Directions as a Function of Angle θ for the 75Fe-15Co-10Al Alloy

Figure 3.4   Saturation Magnetostriction Measured in the
             [100], [110], and [111] Directions as a
             Function of Angle θ for the 85Fe-10Co-5Al
             alloy

Figure 3.5   Saturation Magnetostriction Measured in the
             [100], [110], and [111] Directions as a
             Function of Angle θ for the 80Fe-10Co-10Al
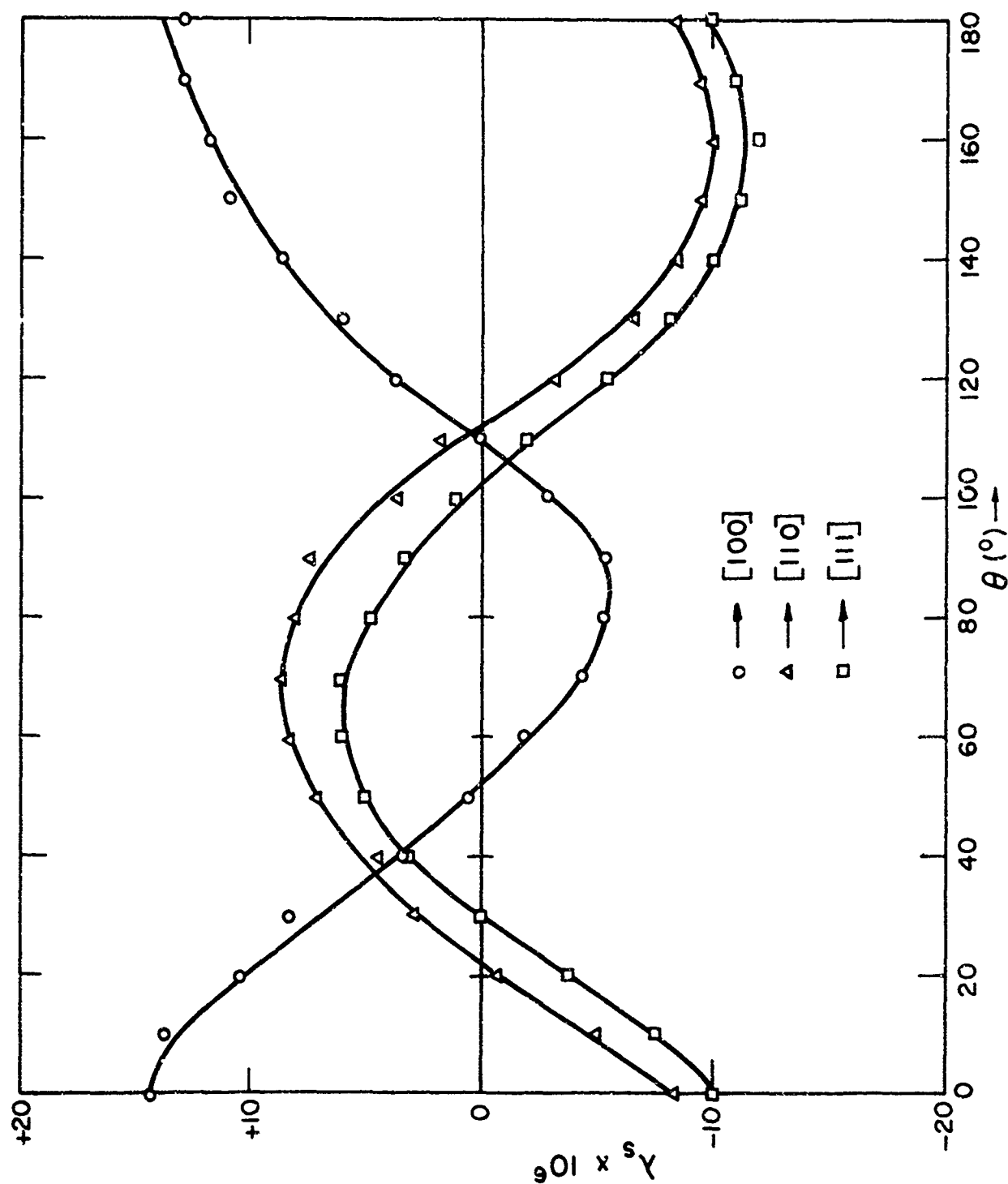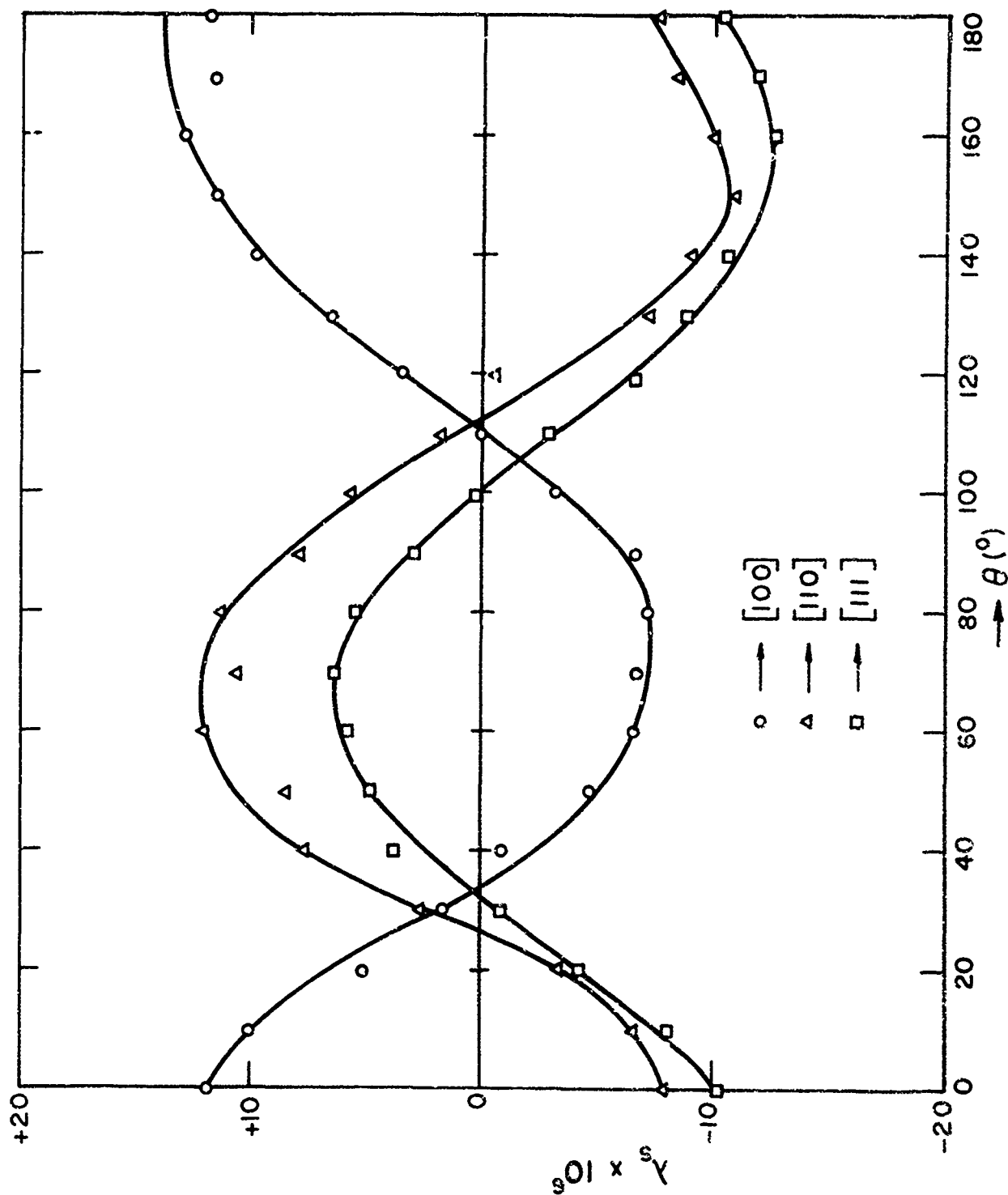   Alloy

Figure 3.6   Saturation Magnetostriction Measured in the
              [100], [110], and [111] Directions as a
              Function of Angle θ for the 80Fe-15Co-5Al
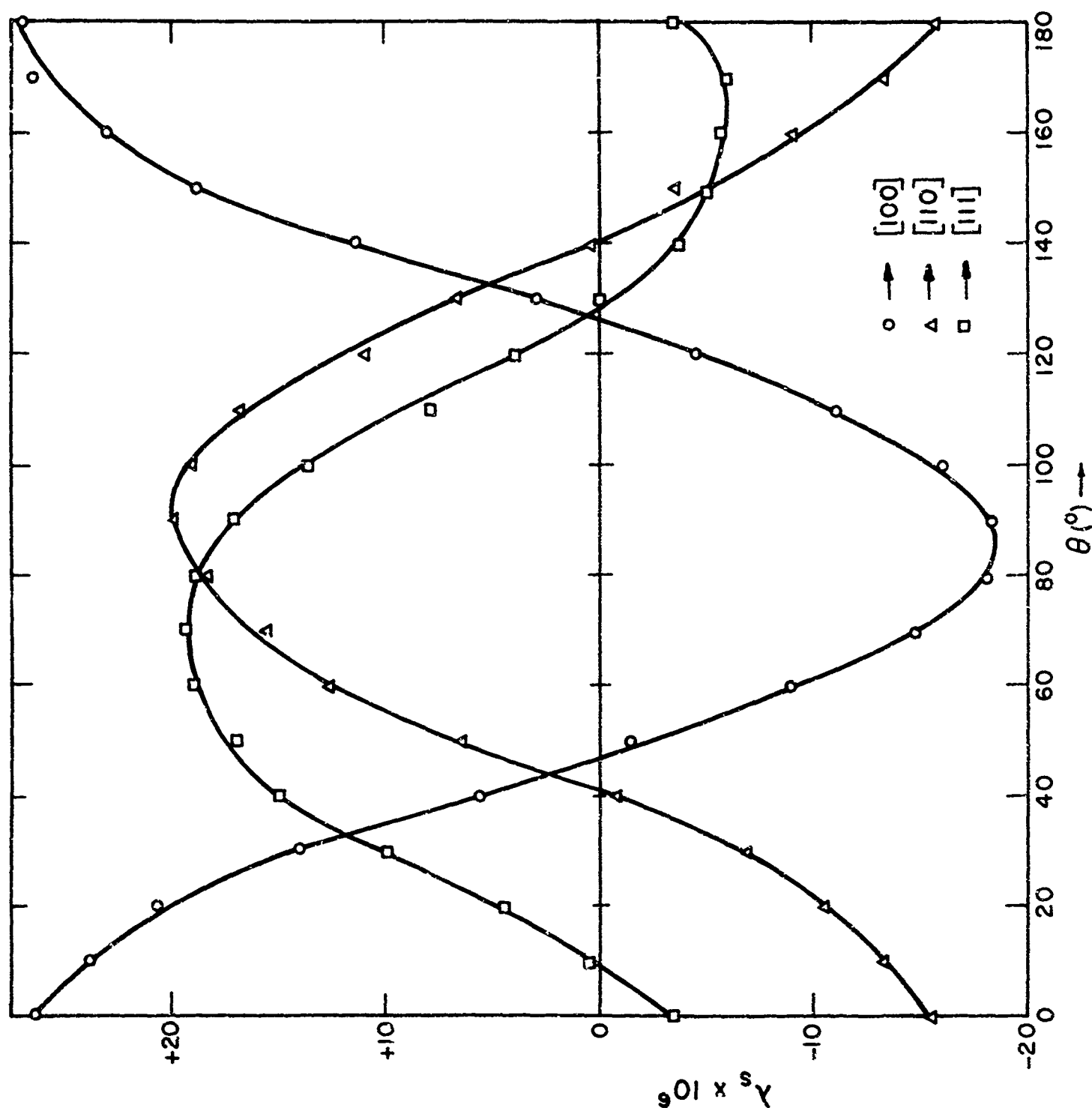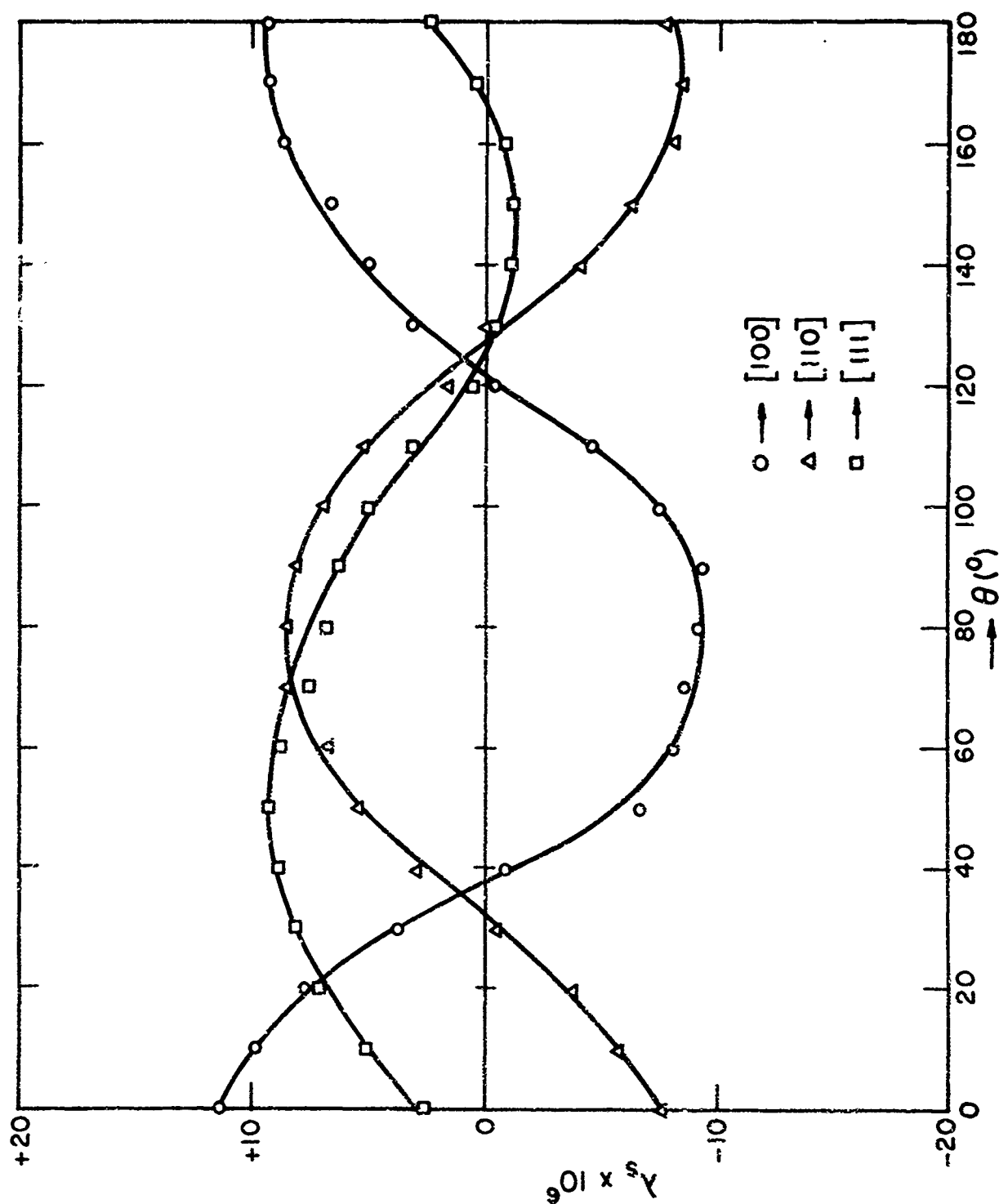   Alloy

$$h_1{}_{(cor)} = -1/3\mu M_s{}^2 (S_{11}-S_{12})$$

$$h_2{}_{(cor)} = -1/6\mu M_s{}^2 S_{44}$$

where

$$\mu = (3\pi/2\epsilon^2)\,[(1-\epsilon^2)\,(3+2\epsilon^2) - (3/\epsilon)\,(1-\epsilon^2)^{1/2}\,\sin^{-1}\epsilon]$$

$$a = b = c/(1-\epsilon^2)^{1/2}$$

In these expressions, M_s is the saturation magnetization, the values of S are the various elastic constants which were taken to be those of iron, a, b, and c are the axes of the disk, and ϵ is the eccentricity. This correction for the so-called form effect was found to be small for these alloys and was not applied.

3.4 Magnetization Studies

The vibrating sample magnetometer yielded total sample moment in emu's vs. external applied magnetic field data for magnetization in the [100], [111], and [110] directions. This raw data was processed by a computer and converted to magnetization (magnetic per unit volume) vs. internal magnetic field information. This information was plotted and the area between the magnetization curves and the ordinate axis determined. This area is proportioned to the energy stored in the crystal during magnetization:

$$W = \int_0^{M_s} H\,dM$$

Where W is the energy stored, M_s is the saturation magnetization, H is the internal field and dM is a magnetization

increment. With this information the various magnetic
anistropy constants were determined from [10]:

$$K_0 = W_{100}$$

$$K_1 = 4(W_{110} - W_{100})$$

$$K_2 = 27(W_{111} - W_{100}) - 36(W_{110} - W_{100})$$

Where the K's are the various principle anisotropy constants
and the W's are the energies required for magnetization in
the specific direction, Table 3.3 lists the values of K_1
obtained for the alloys studied in addition to the sat-
uration magnetization values obtained.

Table 3.3

Saturation magnetization and anisotropy of several crystals

Composition wt.% Fe-Co-Al	Saturation magnetization, M_s (emu/cc at 20°C)	Anistropy constant, K_1 (ergs/cc)
75-15-10	1090	79,000
85-10- 5	1400	2,000
80-10-10	1340	282,000
80-15- 5	1330	39,000

CONCLUSIONS

1. The saturation magnetostriction observed in Fe rich Fe-Al and Fe-Co alloys is not a simple additive property that is enhanced by formation of the Fe-Co-Al alloys. In general, just the opposite appears to be true in that the saturation magnetostriction values observed for the Fe-Co-Al alloys studied are many times smaller than those observed in the binary alloys alone.

2. The magnetic anisotropy of Fe-Co-Al alloys can be controlled over a very wide range of values by composition adjustments.

3. It is observed that for the alloys studied a strong correlation between unit cell volume, K_1, and λp exists. The 80Fe-10Co-10Al alloy has the largest cell size, largest value of K_1 and the largest value of λp. The 85Fe-10Co-5Al alloy is at the other end of the scale while the other alloys occupy predictable positions in between.

BIBLIOGRAPHY

1. R. M. Bozorth, Ferromagnetism (Van Nostrand, New York, 1951), Chapt. 13.

2. C. Kittel, "Physical Theory of Ferromagnetic Domains", Review of Modern Physics, 21, pp. 541-583 (1949).

3. E. W. Lee, "Magnetostriction and Magnetomechanical Effects", Reports on Progress in Physics, 18, pp. 184-229 (1955).

4. C. M. van der Burgt and A. L. Stuijts, "Development in Ferrite Ceramics with Strong Piezo agnetic Coupling", Ultrasonics, 1, 199 (1963).

5. C. A. Clark, "Improved Nickel-Base Alloys for Magneto-strictive Transducers", J. Acoust. Soc. Am., 33, 930 (1961).

6. W. S. Cramer and P. L. Smith, "Piezoceramics for Underwater Sound Transducers", J. Underwater Acoustics (USN), 15, 199 (1965).

7. R. C. Hall, "Magnetostriction of Aluminum-Iron Single Crystals in the Region of 6 to 30 Atomic Percent", J. Appl. Phys., 28, 707 (1957).

8. R. C. Hall, "Single Crystal Anisotropy and Magneto-striction Constants of Several Ferromagnetic Materials Including Alloys of NiFe, SiFe, AlFe, CoNi and CoFe", J. Appl. Phys., 30, 816 (1959).

9. W. J. Carr and R. Smoluchowski, "The Magnetostriction of Single Crystals of Iron-Silicon Alloys", Phys. Rev., 83, 1236 (1951).

10. F. Brailsford, Physical Principles of Magnetism (Van Nostrand, New York, 1966) p. 137.

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
College of Engineering University of Notre Dame Notre Dame, Indiana	Unclassified
	2b. GROUP

3. REPORT TITLE

Magnetostriction and Magnetic Anisotropy in Some Iron Rich Iron-Cobalt-Aluminum Alloys

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Technical Report

5. AUTHOR(S) (First name, middle initial, last name)

Michael E. Kuruzar, Mukund Phadke, and Albert E. Miller

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
February 1970	35	10

8a. CONTRACT OR GRANT NO. ONR-N00014-68-A-0152	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO.	THEMIS-UND-70-6
c. In-House Account No. UND-99850	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. DISTRIBUTION STATEMENT

Document cleared for public release and sale: Its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Department of Navy Office of Naval Research

13. ABSTRACT

ABSTRACT

The magnetic anisotropy and magnetostriction of single crystals and the magnetostriction of some polycrystalline specimens of several Fe rich Fe-Co-Al alloys has been experimentally determined. Specialized apparatus and procedures for alloy preparation, single crystal growth, crystal cutting, crystal orientation, magnetization and magnetostriction studies have been developed.

The first anisotropy constants, K_1, for 75Fe-15Co-10Al (wt.%), 85Fe-1Co-5Al, 80Fe-10Co-10Al and 80Fe-15Co-5Al alloys were found to be 79,000, 2,000, 282,000, and 39,000 (ergs/cc), respectively; the λ_{100} values were found to be $+3.5 \times 10^{-6}$, $+10.6 \times 10^{-6}$, $+19.4 \times 10^{-6}$, and $+17.5 \times 10^{-6}$, respectively; and the λ_{111} values were found to be $+6.2 \times 10^{-6}$, -5.6×10^{-6}, $+9.5 \times 10^{-6}$, and -4.9×10^{-6}, respectively.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Magnetostriction						
Magnetization						
Magnetic Anisotropy						
Iron-Cobalt-Aluminum Alloys						

Security Classification